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XXVII.

CONTRIBUTIONS FROM THE CHEMICAL LABORATORY OF HARVARD COLLEGE.

ON THE CRYSTALLINE STRUCTURE OF IRON METEORITES.

By Oliver Whipple Huntington.

Presented by invitation, May 12, 1886.

The general octahedral structure of iron meteorites was observed soon after the attention of mineralogists had been directed to this remarkable class of bodies.

In the year 1808, Von Widmanstätten * of Vienna observed the crystalline figures brought out on a polished section of the Agram iron by tempering or etching, which have since been known by his name. That these figures might be due to an octahedral structure is said to have been remarked by Berzelius,† and as early as 1816 was inferred by Sömmering from definite measurements of angles between the lines of the figures. In the same year, Wollaston remarked that the iron from Bemdego (Bahia) had an octahedral cleavage,‡ and later, in 1839, still more striking evidences of octahedral structure were described by C. U. Shepard in his paper on the Ashville meteoric iron. § Furthermore, in 1861 Von Reichenbach studied with great detail all the minute features which are presented by the Widmanstättian figures, and published his results in a series of papers in Poggendorff's Annalen entitled "Ueber das innere Gefüge der näheren Bestandtheile des Meteoreisens." ‖ He first made the distinction between the different conditions of nickeliferous iron forming the material of the crystalline plates of which the Widmanstättian figures are sections, and introduced into the descriptions of these bodies the now familiar terms of Balkeneisen,

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* Schweigger's Journ., Bd. lii. p. 172.

† American Journal, 3d series, vol. vi. p. 18.

‡ Philos. Trans. for 1816, p. 281.

§ American Journal of Science, 1st series, vol. xxxvi. p. 82.

‖ Poggendorff's Annalen, Bd. cxiv.

Bandeisen, and Fülleisen, which he also designated respectively as Kamacite, Taenite, and Plessite.

In the year 1864, Gustav Rose, in his "Beschreibung und Eintheilung der Meteoriten," distinctly pointed out the octahedral arrangement of the plates which form the Widmanstättian figures, and compared the structure of meteoric iron with the lamellar structure of many leucite and magnetite crystals, regarding the crystalline mass as consisting of scales or plates of iron separated by laminæ of the iron and nickel alloy which Reichenbach called Taenite.

In 1848, Neumann,* in studying the structure of the Hauptmannsdorf (Braunau) iron, concluded that the fine linear markings which appear on etching the faces of the remarkable cubic forms obtained by fracture were essentially distinct from the Widmanstättian figures, and such lines have since been known as Neumann lines, and have been supposed to indicate a cubic structure, just as the Widmanstättian figures had been supposed to mark solely an octahedral structure.

On this basis, iron meteorites are now generally classified under two chief groups, as the octahedral and the cubic. This distinction, originally made by Gustav Rose, has been brought into prominence by Dr. Brezina in his recent catalogue of the collection of meteorites at the Vienna Museum, and in this catalogue both the cubic and octahedral meteorites have been further subdivided by him into numerous sub-groups, marked solely by the width and other features of the figures or lines.

That such a classification cannot be natural or fundamental is shown by the disagreement of equally competent observers in regard to the character of the figures or lines in special cases, and also by the circumstance that the figures may appear very differently on separate masses of the same fall, and even on different parts of the same section. For example, the iron from Ovifack, Greenland, in regard to whose meteoric origin there has been so much question, is described both by Dr. J. Lawrence Smith and Daubrée as yielding distinct well-marked Widmanstättian figures, while Dr. Brezina insists that it shows absolutely none. In like manner, the well-known iron of Santa Catarina is described by Daubrée, Damour, and others, as exhibiting distinct Widmanstättian figures, while Dr. Brezina not only asserts that no figures could be developed on any specimens which have come under his notice, but even calls in question the discrimination of the eminent mineralogist just quoted. Again, Dr. Brezina, in criticising some observations of Dr. Walter Flight of the British

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* Naturwiss. Abhandlung ber. v. Haidinger, Bd. iii. Abth. ii. p. 45.

Museum, includes the iron of Babb's Mill among those which exhibit no Widmanstättian figures; but the specimens, of unquestionable authenticity, in the collection of Harvard College show well-marked figures. Furthermore, an etched surface on a mass of Nelson County iron weighing 6,800 grammes, and measuring 13 inches in its longest dimension, presents perfectly distinct figures near the centre of the section, which grow indistinct near the edges, and entirely fade out at one end. On the other hand, the iron of La Caille, classed by Dr. Flight with the irons giving no figures, shows, as Dr. Brezina truly remarks, very well developed figures when the sections are made in most directions; but we have etched surfaces of this meteorite which over several square inches of area show no figures whatever.

In view of such differences of observation and opinion as the above examples indicate, it seemed desirable to make a still further study of the crystalline structure of iron meteorites, and Professor Cooke placed at my disposal for this purpose the very large collection of Harvard College, which, since the acquisition of the collection of the late Dr. J. Lawrence Smith, has representatives of all the characteristic meteorites of this class. The writer has been familiar with this collection since it was acquired by the College, and, in examining the specimens from time to time, he has been struck by the indications of crystalline form which many of them present. These appear like rough octahedrons, and their irregular faces present the most striking similarity to cleavage planes, although in some cases the surfaces are covered and the edges rounded by a fused crust. On further examination, it appeared evident that the surfaces in question must be true crystalline faces, for not only were these faces parallel to planes of fracture as indicated by rifts through the mass, but they also stood in a definite relation to the Widmanstättian figures. Moreover, rifts of fracture were common when no external crystalline form could be made out, and hence came the idea of using the cleavage faces as planes of reference in studying the crystalline structure of the iron meteorites; and the plan was formed to grind, polish, and etch surfaces either parallel to the cleavage planes or in a known position towards them, with the hope that it might thus be possible to determine with certainty the relations of the crystalline plates whose cross-sections form the Widmanstättian figures. This was in general the plan of the investigation whose results are here given.

The most striking example of such a rude cleavage form as has been described is a mass of the Franklin County (Kentucky) iron weighing 7,260 grammes, which shows all the planes of an octahedron, inclined to each other at the regular octahedral angle (109° 28′) as nearly as the uneven surfaces of the faces would admit of measurement with an application goniometer. This large, unique, isolated octahedron, of massive iron, measures seven inches in its longest dimension, and one of the triangular faces distinctly outlined measures over four inches on each edge. Another face, still more distinctly marked, measures three inches on each edge. At various points there are triangular depressions or reliefs conforming to the general outline, features which are so characteristic of large crystals; and there are also numerous rifts parallel to the octahedral faces. A large part of the surface is covered with a crust, and, on the basis of the usual interpretation of meteoric phenomena, it is obvious that this crystal is the fragment of an iron meteorite broken up after entering the atmosphere, but while still moving rapidly enough to produce a melted crust over the surface of fracture.

Another example in the Harvard collection of external octahedral form is a specimen of the Carthage (Smith Co.) iron. This specimen shows six faces of a rough octahedron, one of the faces having an area of seven square inches. One half of this octahedron has been partially torn apart into numerous smaller crystals, some of them an inch or more in diameter; but though the crevasses between the individuals are in some places nearly a quarter of an inch in breadth, yet they are bound firmly together by a network of plates, which in some parts raggedly jut out from the octahedral faces. The general appearance of the exterior of the specimen reminds one somewhat of a rough mass of galena crystals, only of octahedral form. The rough crystal is evidently the result of fracture, probably caused during the passage of the mass through the air, and the octahedral faces are cleavage planes, if the term cleavage may be applied to such fractures, which cannot be reproduced by splitting in the ordinary way on account of the malleability of the mass. The specimen further exhibits a fused crust over the octahedral faces, which must have formed after the partial breaking up of the large mass, giving a rounded appearance to the edges. On a polished surface, cut nearly parallel to the largest octahedral face, the figures produced by etching appear very strikingly. They are perfectly distinct and regular, being typical Widmanstättian figures; but when they come to the cracked portion of the iron, they appear as separate plates, some having been broken by the rupture, others separated, while the greater number appear bent and strained, but still coherent and binding the mass firmly together. The whole appearance on the etched surface gives at once the idea of a forcible explosion, and yet all the cracks, even the most ragged, follow directions parallel to the octahedral faces.

A second specimen of the same iron, measuring twelve and a half inches in its longest dimension, and weighing 9,980 grammes, is a very remarkable mass of cleavage octahedrons, loosely packed together and piled on top of each other, not unlike crystals of alum, and almost as sharply defined. The largest octahedral face measures five inches in diameter, but is made up of numerous smaller crystals, in some places jutting out and in others receding, forming numerous triangular projections and depressions.

Another striking octahedral mass is a fragment of the well-known De Kalb County meteorite. One specimen of this iron shows hollow octahedral faces, two inches in diameter, like hopper crystals, consisting of skeletons built up of a series of plates about half an inch wide and one sixteenth of an inch thick. These plates, when cut transversely, constitute the Widmanstättian figures. When the section is cut at random, the figures may differ somewhat in character, and the plates appear to make various angles with each other; but when the etched surface is parallel to an octahedral face, the Widmanstättian figures all make equilateral triangles, their sides being parallel to the octahedral edges.

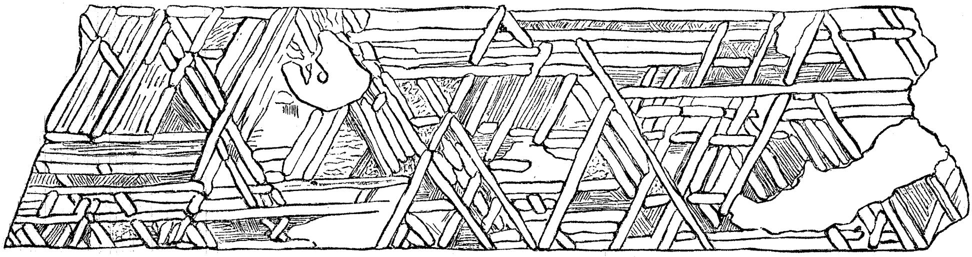

Fig. 1. De Kalb County.

Such a section is shown in Fig. 1, which is part of a surface cut parallel to an octahedral face of the De Kalb specimen just referred to. The figure is an exact sketch, representing the plates of their natural size. The most noticeable character in the figure is the system of broad bands which divide the mass into equilateral triangles. These are cross-sections of the crystal plates, which, in another part of the specimen, stand out so markedly in forming the hollow-faced octahedrons. These plates consist of the purer iron to which Reichenbach gave the name of Balkeneisen, or Kamacite, and they are separated from the groundmass by a thin layer of iron rich in nickel, called by Reichenbach Bandeisen or Taenite. This material is not readily acted upon by acid, and therefore appears on the etched surface as a bright silvery line along the edge of the kamacite plates. In some meteorites, as in the Cocke County and Sevier County, it occurs in sufficient mass to be easily separable from the plates in the form of a thin elastic foil, while in others it almost wholly disappears. The thin plates of "bandeisen" resist the action of oxidizing agents, as they resist the action of dilute acid, so that, when the surface of the meteorite becomes disintegrated by air and moisture, these plates not unfrequently become loose, and are easily separated. Dr. Lawrence Smith analyzed the material of some plates thus obtained from the Sevier County meteorite, and found in them 27% of nickel. The groundmass consists of what Reichenbach calls Fülleisen, or Plessite. In the present case, the latter is filled with very thin plates, or "combs," in general following the octahedral directions and appearing to be a subsequent crystallization, as if the larger plates had first shot through the mass when in a liquid state, and then, as the interior portions solidified, these also crystallized more or less perfectly, but forming smaller and smaller plates.

Figure 2 shows, double the natural size, one face of a very perfect octahedron broken out from the Putnam County meteorite. This iron appears by oxidation of the surface to break up into octahedrons and acute rhombic prisms. The octahedron represented in Fig. 2 was so loose in its structure that it was necessary first to mount it in pitch before grinding the face in order to prevent the plates from splitting off. Here the character is much the same as in the previous one, except that the plates are smaller, and at the points *a*, *b*, and *c* the iron is perfectly granular, showing no signs of crystallization. Moreover, the groundmass, instead of containing the combs above mentioned, has been broken up by a series of irregular cracks into coarse grains, very much like a mass of crackled glass. Another meteorite which most beautifully illustrates the octahedral arrangement is the Tazewell (Claiborne Co.) iron, Fig. 3. Here the figures brought out by etching are very sharply defined, but are so small that, in some parts of the field, it

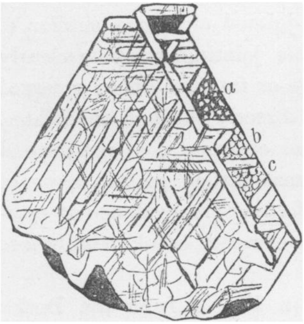

Fig. 2. Putnam Co., Georgia.

seems as if there were almost no limit to the fine bands as seen with an ordinary pocket lens. The bands, though small, exhibit all the features of the coarser Widmanstättian figures. On the exterior of the mass, small octahedral planes are distinctly visible, and a crack, shown by the heavy line in the figure, following the octahedral cleavage, nearly separates the mass into two portions.

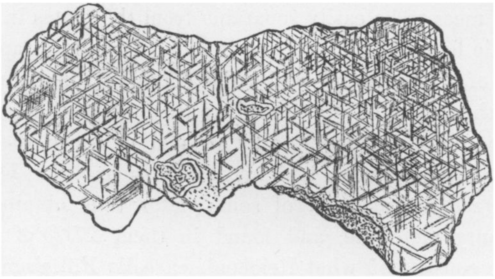

Fig. 3. Tazewell, Claiborne County.*

So far, the observations on octahedral irons do not differ materially from what has been described in the papers already referred to. The Widmanstättian figures are manifestly the evidence of a very perfect crystallization, chiefly in the octahedral form; and these octahedral plates frequently may be readily separated, the successive depositions of the plates producing a more or less jointed structure, similar to that well known in cap-quartz. But this jointing must be clearly distinguished from the octahedral cleavage or fracture above referred to, which, as already stated, often passes directly through the plates. Moreover, the perfection of the octahedral cleavage does not depend upon the size and character of the Widmanstättian plates, many of the irons which show the best figures affording no evidence of octahedral cleavage, while some of the most compact break readily into octahedrons.

An example of the latter is shown in Fig. 4 from the Butler (Bates Co.) iron, where the larger surface, drawn of its original size, shows that the Widmanstättian figures are very fine, and not in broad, distinct plates, while some of them are even microscopic; and yet from this iron was obtained a far more perfect octahedron than from any of those with a coarser structure. The smaller sketch shows one face of such an octahedron, twice the original size. This octahedron showed seven perfectly even regular octahedral faces, the eighth face having been hollowed out where it formed part of the crust of the meteorite.

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* The illustrations of this paper were made by the Lewis Engraving Company, and although in the details they are faithful reproductions of the drawings from which they were taken, yet the lines are all too heavy, and give the idea of a much coarser structure than the meteorites actually present. This is especially true of the above cut.

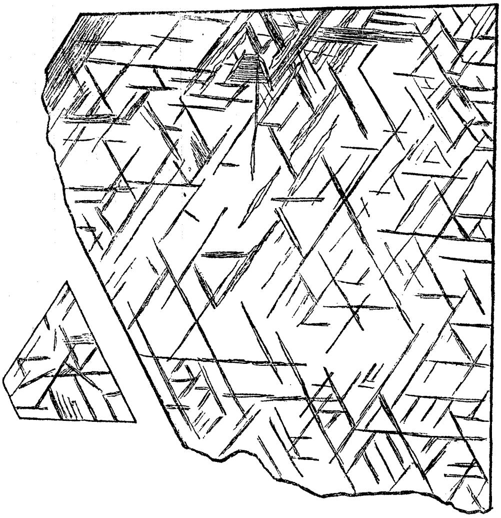

Fig. 4. Butler, Bates County.

All the faces were polished and etched so that the plates might be followed through their entire extent. On examination, it appeared that the majority of the plates, including even the finest microscopic markings, followed the direction of the octahedral faces. But there will be noticed in the sketch of the octahedral face, that, in addition to the usual directions, there appear certain plates which bisect the facial angle of the octahedron. These plates, when followed over an edge on to an adjacent face, were seen to be parallel to an octahedral edge, showing that they must be dodecahedral instead of octahedral.

Thus it at once appeared that the Widmanstättian figures could not be solely characteristic of octahedral structure. Furthermore, the Butler meteorite seemed to stand between well-marked Widmanstättian figures and the finer lines discovered by Neumann and shown by him to be parallel to cube edges. Some of the Butler figures are coarse enough to be classed unquestionably as Widmanstättian, that is, they show the three varieties of iron distinguished by Reichenbach, which he calls the Trias; while others of the figures are almost microscopic markings, in which distinct plates of kamacite and plessite cannot be made out even under the microscope. Between these two extremes there is every gradation. The Butler meteorite has always been classed among the octahedral irons. We come next to the Coahuila, which has been classed with the so-called cubic irons.

A large section of this iron, on being etched, showed innumerable fine lines, seeming at first sight as irregular as the markings on a chopping-block. When this section was examined under the microscope, it showed all the characters of the Butler figures, only a degree finer. On studying the directions of the lines, they appeared to make every possible angle with each other, but with a prevalence of right angles. The meteorite is very compact, with usually no external crystalline form, but it was found that on one specimen, by quick blows of the hammer, cleavage masses could be broken away. One of these cleavage masses is shown, of twice its original size, in Fig. 5. It has the well-known form of the cube twin, described by Tschermak * as typical of the Hauptmannsdorf iron, but with this difference, that the cube in this case is modified by the octahedron. On polishing and etching the crystal faces, the lines appeared so fine as to be for the most part indistinguishable by the naked eye, but under the microscope showing most beautiful markings, all parallel either to the cube edges or to those of the octahedron. Most of the lines were so fine as to appear like the finest striations, while a few, on the other hand, were coarse enough to be recognized by a pocket lens as consisting of plates with all the characters of the finer Widmanstättian figures.

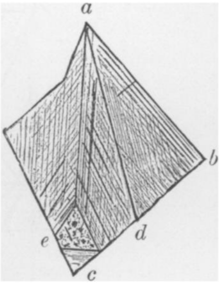

Fig. 5. Coahuila, Mex.

In actual contact with the crystal just described appeared an acute rhombic prism with an angle of about 120°. This prism, shown of twice its size in Fig. 6, could only be separated by the hammer over the area *a b c d*, and the rest of the face had to be continued by cutting through a very compact part of the specimen. *a b*, *b c*, and *c d* are the natural crystal edges, and the three faces of the prism not shown in the figure were chiefly characterized by the system of fine lines seen here parallel to *c b*. The lower of the two drawings was made from the original specimen, without a knowledge of what the angles were; but on examination it was found that the lines, and prism faces as well, could all be referred to a cube with twin members on all the trigonal axes.

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* Akademie der Wissenschaften Wien, Bd. lxx. Abth. i. p. 449.

The face of such a twin is represented by the diagram between the two figures of the crystal, and the upper figure was actually drawn from the cube diagram by means of a parallel ruler, and it will at once be seen from the close coincidence of the two figures that the upper one must be correct, the lower one only varying within the limit of error of a mechanical drawing.

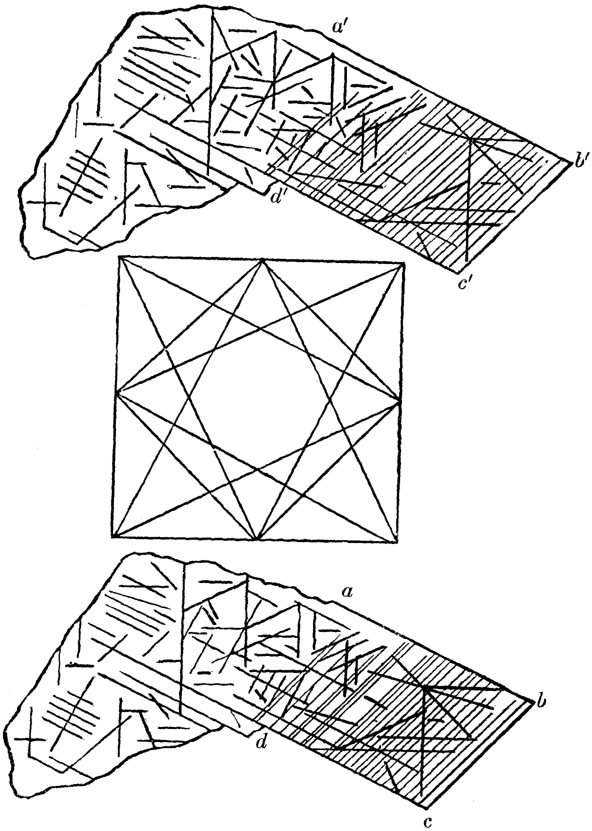

Fig. 6. Coahuila, Mexico.

On examining the Hauptmannsdorf iron, which has long been known to break with a cubic fracture, a cube face under the microscope appeared, as shown in Fig. 7, some of the lines being parallel to the cube edges and others forming diagonals of the cube face. These diagonals might be octahedral lines or dodecahedral lines, or they might be lines of cleavage parallel to the face of the other individual of a twin, and as the face shown in section replacing the cube angle at *a* was the face of a twin cube, the lines parallel to that edge would probably be due to the same plane; and this was proved to be the case, as on an adjacent face the same lines followed the direction of twinning. These lines of twinning are not represented in Fig. 7, to prevent confusion.

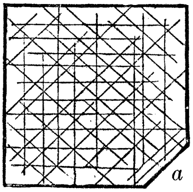

Fig. 7. Hauptmannsdorf (Braunau).

Thus the Hauptmannsdorf iron appears to be purely cubic in structure, while the Tazewell appears to be purely octahedral. However, as the octahedron was observed in the Coahuila iron, and the dodecahedron appeared in the Butler iron, it became a question whether the cube and dodecahedron could not be found in the typical octahedral irons. A very large number of irons were studied with this end in view, but nothing could be determined with specimens where only one face could be examined. It was necessary to have two known crystal faces, and to be able to follow the plates over an edge. For on a cube face the octahedral plates give rectangular intersections, while on an octahedral face the cube plates would give intersections parallel to the octahedral edges.

Figure 8 shows of original size a section of the well-known La Caille meteorite, cut parallel to an assumed cube face, the direction being determined by external well-developed octahedral faces. Here the rectangular intersections *a c* and *c d* result from octahedral plates intersecting the cube face, but there are also diagonals of this rectangle. The plate *a b* and those parallel to it make an angle of 45° with *c d*, and when traced on to an adjacent face, cut at right angles to the one in the figure, they follow the direction of a dodecahedral plane, and on the under side of the specimen there appeared a large natural face, an inch in diameter, exactly parallel to this same plate. This face meas-

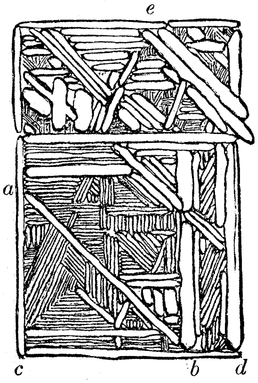

Fig. 8. La Caille.

ured, as shown by an application goniometer, 145° with an adjacent octahedral face, showing that it was the face of a dodecahedron truncating the octahedral edge; and when etched neither of these faces showed any Widmanstättian figures, but only a mottled appearance, as is usually the case with a surface consisting of a single plate. The other oblique lines in the direction *c e* make an angle of 66° 19′ with *c d*, and are plates of the twin octahedron corresponding to the twin cube before mentioned.

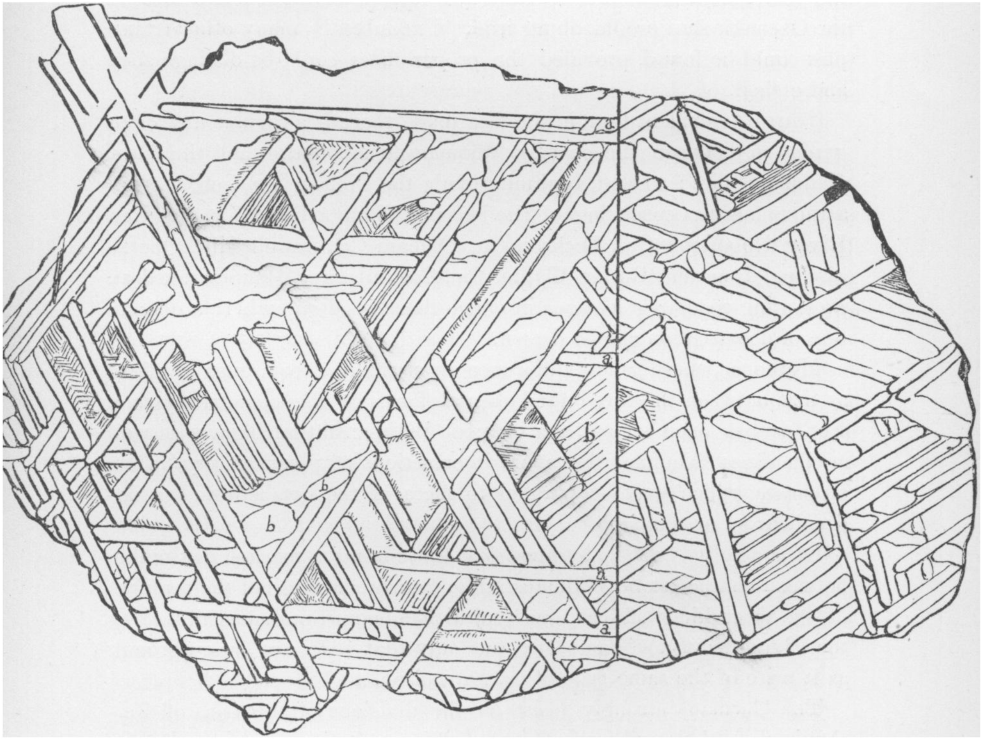

Fig. 9. Robertson County.

Figure 9 shows, of original size, two sections of the Robertson County iron. The left-hand half of the figure is parallel to the octahedral face, while the right-hand half is a face at right angles to the first, and in the upper left-hand corner is shown an octahedral cleavage. Here most of the plates are octahedral, and are at once recognized, but the plates marked *b* and also the irregular cloudy-looking masses bisect the octahedral angle, and these follow a dodecahedral direction, while the plates marked *a* on the octahedral face are parallel to a lateral edge, and, on following the plates on to the face at right angles to the first, it will be seen that they continue to be parallel to the lateral edge. Hence they cannot be octahedral plates, and, since they are parallel to a principal section of the octahedron, they must be cubic. In order to see whether the Robertson County iron was an unusual case of cubic plates, other well-marked Widmanstättian irons were examined and in the same way the cube was found, together with the dodecahedron, in the De Kalb iron before mentioned, and also in the Obernkirchen or Oldenburg iron. Undoubtedly, many other examples could be found, provided the proper faces could be distinguished and etched.

Thus it is evident that, in the first place, there is a regular unbroken gradation between the coarsest Widmanstättian figures and the finest Neumann lines; so that, beginning with the Nelson Co. iron, we can arrange a series consisting of the irons of Wichita Co., Glorietta, Red River, Robertson Co., Dickson Co., Oldham Co., Jewell Hill, Obernkirchen, Tazewell, Butler, Walker Co., Coahuila, and Hauptmannsdorf, presenting regular gradations in which there is no gap where a definite line of demarcation can be drawn.

Moreover, there is no difference in crystalline form even so slight as that between the three fundamental forms of the isometric system. For, as has been shown, the coarsest Widmanstättian figures as well as the finest Neumann lines are intersections of planes of crystalline structure, which may be parallel to faces of the octahedron, the dodecahedron, or the cube.

Of course it is not maintained that there is not a marked distinction between characteristic Widmanstättian figures showing all the features of the three kinds of iron, and typical Neumann lines as exhibited by the Hauptmannsdorf meteorite, but only that both are an outgrowth as it were of the same type of crystallization.

The Germans strongly insist on the divisions of the trias of Reichenbach, and describe the features of kamacite, taenite, and plessite as if they were essentially different substances, instead of merely different conditions of a nickeliferous iron; and the only evidence we have that there is any material difference of composition is based on an analysis cited by Reichenbach* of the so-called taenite plates, which he had mechanically separated from the Cosby Creek iron, and which were found to contain 13.8 per cent of nickel, while the mass as a whole only contained 9.8; and, on this ground, it is assumed that kamacite consists of a purer iron. As stated above, Dr. Lawrence Smith found in plates obtained from the Sevier County iron, which is closely allied, if not identical, with the Cosby Creek, 27 per cent of nickel. This supposition would harmonize with our idea of the manner in which crystallization takes place. For though a substance in crystallizing may include foreign substances, still crystallization is a purifying process. Hence, as the molten metal cooled, there would be a tendency for the pure iron to crystallize first, thus forcing back, as it were, a less pure material, which would solidify subsequently; and the natural alternation of such stages, during a very slow process of crystallization, would result in a succession of plates of comparatively pure metal interlaminated with a richer nickel-iron alloy.

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* Poggendorff's Annalen, Bd. cxiv. p. 258.

This theory is strongly supported by the structure of the Pallasites, where the iron occurs surrounding masses of olivine. Here, as Reichenbach has so beautifully shown,* the silicate grains are first surrounded by a deposit of kamacite, and the trias does not appear till this layer of the purer iron has been deposited.

Moreover, Tschermak has shown,† in regard to artificial irons, that pure iron tends towards a cubic crystallization with markings similar to the Hauptmansdorf meteorite, while impure iron, like cast-iron, frequently shows imperfect octahedrons and a scaly structure, not unlike that of many meteorites, and this becomes very striking in the so-called Spiegeleisen.

We know as yet very little of the causes which determine the crystallization of substances with an isometric structure in one or another of the three fundamental forms, but we do know that constantly the presence of some foreign material in the crystallizing menstruum produces a marked influence on the result. Thus, common salt, which usually crystallizes in cubes, crystallizes in octahedrons from solutions containing urea. Then again, galena may crystallize under unknown conditions in all three of the fundamental forms. Indeed, the crystallization of galena presents a striking analogy to that of iron as it appears in meteorites. It was shown many years ago, by Professor Cooke,‡ that galena, like the iron, may be cleaved parallel to faces of all three fundamental forms. Usually the cubic cleavage is the most pronounced; but in the remarkable variety from Lebanon County, Pennsylvania, the octahedral cleavage is the more eminent, although both the cubic and dodecahedral can also be easily obtained.

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* Poggendorff's Annalen, Bd. cxiv. p. 99.

† Akademie der Wissenschaften Wien, Bd. lxx. Abth. i. p. 447.

‡ American Journal of Science, 2d series, vol. xxxv. p. 127.

In connection with this, it is interesting to note that, on polishing and etching octahedral, dodecahedral, and cubic faces on crystals of galena, lines were developed precisely similar in character and position to the Neumann lines. Now it is to be remarked that on the cube faces of the Hauptmannsdorf iron, which Reichenbach regards as consisting of kamacite only, — that is, the purest form of iron, — we have a prevailing cubic structure, as indicated by the so-called Neumann lines. But in proportion as the iron in the process of crystallization has excluded foreign material, as shown by inclusions such as graphite, sulphide of iron (troilite), phosphide of iron (Schreibersite) and the like, the octahedral form prevails.

It is further to be noticed in this connection, that on the sections of kamacite plates in characteristic octahedral irons fine lines appear called "Schraffirungs" by the Germans, which are evidently identical with the Neumann lines, and these follow the direction of the prevailing crystalline form. Hence, on this view, the coarser structure which gives rise to the Widmanstättian figures with the well-marked trias of Reichenbach is connected with the exclusion of incompatible material in the process of crystallization, while the more uniform structure of the so-called cubic meteorites, marked by the Neumann lines, depends on the circumstance that the material was susceptible of crystallization as a whole. It is by no means necessary that, to fulfil this condition, the material should be pure iron. It may be an alloy capable of crystallizing in mass, as is the case with many crystalline alloys.

We conclude, then, that the crystalline structure of the coarsest octahedral irons is not more definite than that of the cubic irons; but in the first case the process of crystallization determines the elimination of the various materials which form the Widmanstättian plates, while in the second case no such elimination takes place, and between these extremes there is every gradation. The element of time may also be an important, and perhaps the chief, condition in determining the result, for we should naturally expect that, during a very slow crystallization, foreign material would be more completely eliminated than during a process which was comparatively rapid. That the crystalline structure is equally definite in both cases, is shown by the fact that cleavage forms may be developed with equal readiness in either class of irons.

Though there are no very definite data in regard to the crystallization of nickeliferous alloys, yet it has been suggested that the presence of nickel in the meteoric iron might determine its crystallization. It has been thought that between certain limits in the per cent of nickel present octahedral structure might result, while with a different amount of nickel the crystallization would be cubic. With an idea of determining this point if possible, the analyses of eighty meteoric irons, as given in various scientific journals, were tabulated according to their per cent of nickel, and at the same time the size and character of the figures produced by etching were noted. Unfortunately, these results appeared so discordant that no trustworthy conclusion could be drawn from them, for it was frequently the case that the composition of the same meteorite as given by equally competent analysts differed by several per cent. Thus the per cent of nickel in the Babb's Mill meteorite has been variously stated as 14.7, 17.1, 4.7, and 12.4, and yet this appears to be a perfectly homogeneous iron.

Dr. Flight of the British Museum has made the remark, that Widmanstättian figures seldom appear in irons containing more than nine per cent of nickel, and it seems to be true that most of the irons giving well-marked Widmanstättian figures contain from five to nine per cent of nickel, though they vary all the way from 3.12 to 17.37 per cent. On the other hand, the irons giving well-marked Neumann lines contain generally only five or six per cent of nickel, but the data at present are insufficient to afford any basis for generalization.

Moreover, it is by no means as yet established that the amount of nickel present is the cause which determines the difference of feature in the crystallization of meteoric irons, nor should we be led to infer that such would be the case from the behavior of alloys of metals so closely allied as nickel and iron. It is certainly quite as probable that the effect may be due to some other impurity, — for example, to the presence of phosphorus, which is known to produce such marked effects on the physical properties of iron. According to the analysis of Reichenbach already cited, the taenite plates of the Cosby Creek meteorite contain 0.295 per cent of phosphorus, while the mass only contains 0.089 per cent, and it is well known that Schreibersite, which is a phosphuret of iron containing fourteen per cent of phosphorus, constantly appears on sections of meteoric iron, in lines along the bands of kamacite. But our knowledge of the amount of phosphorus in the different meteorites is even less complete than our knowledge of the per cent of nickel. We do not know, in regard to any of the impurities, either the average amount in any considerable portion of the meteoric mass, or to what extent the amount varies in different portions of the same mass. The most we know, in any case, is the composition of one or more fragments selected for analysis, and, as we have shown, even these data are so discordant as to be wholly untrustworthy. It is impossible to infer with certainty from the descriptions whether the disagreement arises from faulty methods of analysis, or from actual difference of composition in the fragments selected, and no satisfactory conclusions can be reached in regard to the influence of impurities on the crystalline structure, until an extended series of systematic analyses has been made of the iron meteorites, by processes which have been well considered, and the limits of whose accuracy have been carefully determined. In such a chemical investigation, regard should be paid to the probable variation in composition of different parts of the mass. This is a subject to which we hope to return at a future time.

The action of the process of crystallization in eliminating impurities produces effects with many minerals not unlike those of the Widmanstättian figures. Very striking exhibitions of such effects may be seen with the microscope in rock-sections containing crystals of leucite, nosean, nepheline, and other minerals. Illustrations of these phenomena have been given in works on lithology, and it is only necessary to allude to them here, in order to make clear their analogy with the phenomena we are studying. But a far more striking illustration of this similarity is shown by a large specimen of fluorite in the Harvard collection, which has been cut through a mass of compacted crystals. The polished surface imitates very closely the features of the Widmanstättian figures. There are distinct bands, marked by difference of color instead of difference of lustre, separated from the groundmass of the mineral by definite layers of less pure material. The bands are about the width of those in the Glorietta meteorite, and they all appear alike, bordered in every case by the same layers of impurities arranged in a definite order, and these bands, crossing at various angles, with a predominance of right angles, bear a most striking resemblance to the Widmanstättian figures. Such examples as these indicate clearly that the Widmanstättian figures are not a peculiar phenomenon, but that such an alternation of plates is often a characteristic of crystalline structure, when the process of crystallization is attended by the elimination of foreign material.

There is another feature of the Widmanstättian figures which often appears, and which is best explained by the assumption that the process of crystallization was extremely slow. Figure 10 shows two faces of a very perfect octahedron, drawn of original size, from the Cranberry Plains (Poplar Camp) iron. It will be seen by this sketch that the octahedral outline has been sharply formed; but while many of the Widmanstättian plates are parallel to this outline, there are others which are markedly curved. These curved plates must have originally formed through the liquid mass as true planes, like their neighbors, and have been bent in the subsequent solidifying of the remaining material. For, if they had been distorted by an exterior force, the regularity of the octahedron would have been at the same time destroyed.

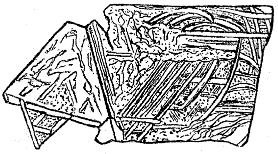

Fig. 10. Cranberry Plains.

This phenomenon of curved plates has been made a basis of subdivision in the classification of iron meteorites. But it is evident from the figure that the bending is not a constant or essential character, as the plates are not all curved, but only appear so at particular parts of the mass, and some specimens show no trace of such a feature. In a word, such curved plates are simply accidents of the crystallization. Very similar bending is common in various minerals, as in gypsum, and very conspicuously in the beautiful crystals of stibnite which within the few last years have been brought from Japan.

A similar remark might be made in regard to the swellings formed in the kamacite plates around inclusions of troilite, Schreibersite, and the like, which have been so minutely described by Reichenbach, and named by him "Wülsteisen."* These again are accidents of crystallization, which have their counterpart in other crystals, and are most beautifully shown on the plates of mica from Chandler's Hollow, Delaware, where the depositions of magnetic oxide of iron on the planes of the crystalline growth of the mica produce effects which imitate in a most striking manner the Widmanstättian figures.

We give in Fig. 11 as perfect a representation of one of these mica plates as could be obtained by the photographic process used in illustrating this paper, and it will be seen that the resemblance is very close. The analogy here is far more than superficial, and shows, as we conceive, the mode of action by which the Widmanstättian figures were produced. This will be evident if it is borne in mind that the figures on the mica plate are also sections of planes of crystalline growth on which the particles of oxide of iron eliminated during the process were deposited. Of course, the mere resemblance in the outline of the two sets of figures is accidental, and arises from the circumstance that the planes of crystalline growth of muscovite mica are parallel to a rhombic prism of sixty and one hundred and twenty degree angles, the right section of such a prism being similar to the section of a regular octahedron parallel to one of its faces.

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* Poggendorff's Annalen, 1861, Bd. cxiv. p. 477.

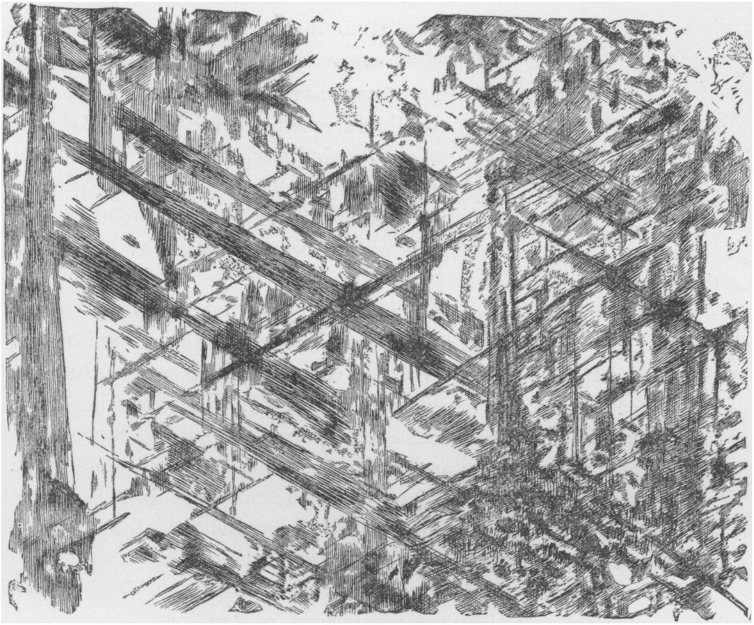

Fig. 11. Mica, Chandler's Hollow, Delaware.

The conditions of the plessite which fills the cavities between the crystalline plates of iron meteorites also present features which are especially characteristic of the crystallization of alloys. Sometimes the space is packed with small crystalline plates parallel to those of the external form, the combs already mentioned, shown in Fig. 1. Again the material is granular, as shown at *a*, *b*, and *c*, Fig. 2, or again divided into polygonal masses as shown in the same figure. Similar features in the alloys of zinc and antimony have been described by Professor Cooke,* and in the alloys of copper and zinc by Prof. F. H. Storer.† They correspond to that pasty condition so well known to plumbers and workers in alloys. We here refer only to the conditions of the plessite; but at times we also find the whole meteoric mass divided up by small cracks, and thus rendered so friable that it can readily be broken into coarse polygonal grains with a hammer. Such a disintegration must have been a mechanical one, affecting the whole mass subsequent to its solidification. It is similar to the well-known effects produced on iron by long-continued jarring, and may have been the result of the violent concussions which are known to be caused by the passage of the meteorite through the air. We have recently had the opportunity of examining a specimen of aluminum bronze sent to the Laboratory of Harvard College by Prof. C. F. Mabery of Cleveland, Ohio, which most strikingly illustrates the effect here described. The bronze, consisting of 90% copper and 10% aluminum, had been cast into a bar and re-heated for forging. When the heated bar was laid on an anvil and struck with a hammer, it broke up into small polygonal grains, just like those of the Cosby's Creek and Seelasgen meteorites.

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* Memoirs of the American Academy, New Series, vol. v. pp. 336–371.

† Ibid., vol. viii. pp. 27–56.

Such products as have been described all point to a very slow cooling of the molten metal out of which the crystals came, and this is the opinion held by the best observers in regard to this process. Thus Mr. Sorby writes: "These facts clearly indicate that the Widmanstätt's figuring is the result of such a complete separation of the constituents, and perfect crystallization, as can occur only when the process takes place slowly and gradually. They appear to me to show that meteoric iron was kept for a long time at a heat just below the point of fusion, and that we should be by no means justified in concluding that it was not previously melted. Similar principles are applicable in the case of the iron masses found in Disco; and it by no means follows that they are meteoric, because they show the Widmanstätt's figuring. Difference in the rate of cooling would serve very well to explain the difference in the structure of some meteoric irons, which do not differ in chemical composition; but as far as the general structure is concerned, I think that we are quite at liberty to conclude that all may have been melted, if this will better explain other phenomena." * Similar opinions have been expressed by Tschermak and Haidinger.

We have tried in this paper to establish the following points: —

First. That many of the masses of meteoric iron in our collec-

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* Nature, 1877, vol. xv. p. 498.

tions are cleavage crystals, broken off probably by the impact of the mass against the atmosphere.

Secondly. That these masses show cleavages parallel to the planes of all the three fundamental forms of the isometric or regular system, namely, the octahedron, the cube, and the dodecahedron.

Thirdly. That the Widmanstättian figures and Neumann lines are sections of planes of crystalline growth parallel to the same three fundamental forms of the isometric system.

Fourthly. That on different sections of meteorites Widmanstättian figures and Neumann lines can be exhibited in every gradation, from the broadest bands to the finest markings, with no break where a natural line of division can be drawn.

Fifthly. That the features of the Widmanstättian figures are due to the eliminations of incompatible material during the process of crystallization.

This investigation throws no new light upon the origin of meteorites, except so far as it strengthens the opinion that the process of crystallization must have been extremely slow. The occurrence of large masses of native iron occluding hydrogen gas, and containing nickel, cobalt, phosphorus, sulphur, etc., implies a combination of conditions which the spectroscope indicates as actually realized in our own sun and in other suns among the fixed stars, and the most probable theory seems to be that these masses were thrown off from such a sun, and that they very slowly cooled, while revolving in a zone of intense heat.

In this paper we have not taken into consideration a number of iron masses, whose meteoric origin has been generally accepted, which show no Widmanstättian figures and not even any Neumann lines. A considerable proportion of these are certainly not meteoric. In the Harvard cabinet there are two specimens, labelled respectively Campbell County, Tennessee, and Hominy Creek, North Carolina, which are evidently nothing but cast-iron, and a third, labelled Tarapaca Hemalga, Chili, which is probably of similar material. We could find on the specimens of this class in the Harvard collection no distinct evidences of crystallization; but also we could find no features incompatible with that unity of structure which it has been the chief object of this paper to illustrate.